

Lethal radiation from nearby supernovae helps to explain the small cosmological constant

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Abstract

The observed value Λ_{obs} of the cosmological constant Λ is extremely smaller than theoretical expectations, and the anthropic argument has been proposed as a solution to this problem because galaxies do not form when $\Lambda \gg \Lambda_{\text{obs}}$. However, the contemporary galaxy formation theory predicts that stars form even with a high value of $\Lambda/\Lambda_{\text{obs}} \sim 50$, which makes the anthropic argument less persuasive. Here we calculate the probability distribution of Λ using a model of cosmological galaxy formation, considering extinction of observers caused by radiation from nearby supernovae. The life survival probability decreases in a large Λ universe because of higher stellar density. Using a reasonable rate of lethal supernovae, we find that the mean expectation value of Λ can be close to Λ_{obs} , and hence this effect may be essential to understand the small but nonzero value of Λ . It is predicted that we are located on the edge of habitable regions about stellar density in the Galaxy, which may be tested by future exoplanet studies.

1 Introduction

The concordance cosmological model including a nonzero cosmological constant, Λ , is accepted as the best description of the universe observed (Weinberg et al. 2013; Bull et al. 2016). However, the observed value Λ_{obs} is smaller than theoretical expectations by at least 50 orders of magnitude. Furthermore, Λ works as the constant energy density of vacuum, and its value is curiously similar to the decreasing matter energy density just now in the long history of the universe. The extreme smallness and coincidence are perhaps the most difficult problem in physics (Carroll 2001; Caldwell and Kamionkowski 2009). Lack of persuasive explanations has motivated to consider the anthropic argument, assuming that Λ is determined by a stochastic process in the early universe. An observer will not appear in a universe of $\Lambda \gg \Lambda_{\text{obs}}$, because structure

formation is suppressed before galaxies form once the cosmic expansion is accelerated by Λ (Barrow and Tipler 1986; Weinberg 1987; Efstathiou 1995; Martel et al. 1998; Garriga et al. 2000; Peacock 2007)¹.

A wide range of theoretical possibilities about stochastic determination of Λ have been discussed (e.g. Polchinski 2006; Totani 2017). Here we consider the simplest version in which Λ is the only random variable while other physical constants and the total amount of matter in the universe are unchanged. Though some theories predict that not only Λ but also other physical constants may change, we leave these possibilities for future studies. If the prior probability distribution $dP_p/d\Lambda$ of Λ extends down to $\Lambda = 0$ with a nonzero value, a natural distribution is flat per unit Λ (i.e. $dP_p/d\Lambda = \text{const.}$)² around $\Lambda = 0$, because physically natural scales of Λ are much larger than Λ_{obs} . In this work we assume this prior distribution following previous studies (e.g., Efstathiou 1995; Martel et al. 1998; Garriga et al. 2000; Peacock 2007). Then the probability distribution of Λ for an observer, $dP_o/d\Lambda$, should be proportional to the number of observers per unit mass of cosmic matter, $n(\Lambda)$. A very small value of $|\Lambda| \ll \Lambda_{\text{obs}}$ is statistically unlikely, and hence the coincidence is also explained. Though Λ can also be negative, the cosmic expansion would be pulled back to collapse before an age of ~ 10 Gyr when $\Lambda \lesssim -\Lambda_{\text{obs}}$, allowing no observer like us in a universe with $\Lambda \ll -\Lambda_{\text{obs}}$. This means that inclusion of negative Λ does not significantly affect the anthropic argument, and we consider the Λ distribution only in $\Lambda > 0$.

More quantitatively, $n(\Lambda)$ can be calculated based on the theory of galaxy formation, if we assume that the number of observers is proportional to stellar mass produced in the universe (Sudoh et al. 2017; Barnes et al. 2018). The calculation of Sudoh et al. (2017) by a semi-

¹ See also Lineweaver & Egan (2007) and Egan and Lineweaver (2008) for anthropic expectation about the ratio of matter to vacuum density of the universe, under the condition that the cosmological constant is the observed value (i.e., $\Lambda = \Lambda_{\text{obs}}$).

² If Λ is bound to be positive, a flat distribution per unit $\ln \Lambda$ may also be possible without any characteristic scale. However, in this case we need to introduce a lower cut-off at $\Lambda \ll \Lambda_{\text{obs}}$, otherwise the distribution is mathematically ill-defined. We do not know any low-energy physics leading to such a cut-off.

analytic model of cosmological galaxy formation (Nagashima and Yoshii 2004) is shown by solid curves in Fig. 1 where $n(\Lambda)$ is calculated by stellar mass³ produced up to a fixed age of the universe (15 Gyr), and the cosmological parameters except for Λ are fixed to the 2015 determination by *Planck* (Planck Collaboration 2016). This model is based on the standard picture of hierarchical structure formation driven by cold dark matter. Dark matter halos are generated by the Monte-Carlo method, so that their formation rate and merger history are consistent with the structure formation theory. Then galaxies grow in dark halos by star formation, which are calculated considering baryonic physics such as gas cooling, supernova feedback, and galaxy mergers. Various observations, including galaxy luminosity functions of local as well as high-redshift galaxies, are broadly consistent with the predictions by this model (Nagashima and Yoshii 2004; Kashikawa et al. 2006; Kobayashi et al. 2007). The predicted distribution of $dP_o/d(\ln \Lambda)$ peaks at $\Lambda \sim 20 \Lambda_{\text{obs}}$, and the distribution extends to $\Lambda \sim 100 \Lambda_{\text{obs}}$. The probability of finding $\Lambda < \Lambda_{\text{obs}}$ is only $P_o(\Lambda < \Lambda_{\text{obs}}) = 6.7\%$. More recently, Barnes et al. (2018) found the distribution peak at $\Lambda/\Lambda_{\text{obs}} = 50\text{--}60$ and $P_o(\Lambda < \Lambda_{\text{obs}}) = 2\%$ using a numerical simulation of galaxy formation, which is roughly consistent with Sudoh et al. considering model uncertainties. This may imply that the value of Λ is not determined by the anthropic mechanism.

However, the amount of star formation is not the only factor to determine the number of observers, but we should also consider planet habitability around a star, which depends on locations and environments in a galaxy (Gonzalez et al. 2001; Lineweaver et al. 2004; Gowanlock et al. 2011; Forgan et al. 2017). Radiation from nearby supernovae is widely discussed as a possible cause of extinction of terrestrial organisms on a planet, because high energy radiation (gamma-rays and cosmic-rays) from a core collapse supernova within ~ 10 pc would have significant effects on the ozone layer (Ruderman 1974; Whitten et al. 1976; Reid et al. 1978;

³Sudoh et al. (2017) also considered a dependence of $n(\Lambda)$ on metallicity, but found that this effect is actually small (see their Fig. 4). This is because low metallicity galaxies are generally dwarf galaxies, and star formation in such galaxies is suppressed by supernova feedback, making their contribution to cosmic stellar mass budget small.

Gehrels et al. 2003). Interestingly, the expected number of such nearby supernovae in the solar neighborhood is of order unity during the time span of terrestrial organisms (~ 0.5 Gyr) in the history of Earth (Gehrels et al. 2003). This coincidence implies that we may be living on the edge of habitable regions concerning stellar density, and an intelligent observer may not be allowed to appear in higher density regions. In this work we make a quantitative assessment of this effect on the probability distribution of Λ .

2 Stellar Densities in Galaxy Formation

The key quantity in galaxy formation to determine stellar density is the internal density of a gravitationally collapsed dark halo. The physics of dark halo formation can be understood by the analytic spherical collapse model (see, e.g. Cooray and Sheth 2002 for a review). The internal density (virial density) after the collapse, ρ_{vir} , does not depend on halo masses but it decreases with cosmic time, as shown in Fig. 2 for various values of Λ . When Λ is large, decreasing energy density of matter becomes lower than Λ in an earlier epoch. After this transition, ρ_{vir} becomes constant, and the number of collapsing halos rapidly decreases. Therefore, in a universe with $\Lambda = 50 \Lambda_{\text{obs}}$, internal density of any dark halo is more than 10 times higher than that of a halo collapsing at a cosmic time of 10 Gyr in the universe that we observe. Stars are expected to form only after the hot diffuse gas in a halo cools and contracts, but the final size of a rotationally supported gas disk is proportional to the virial radius of the host dark halo, because the mean specific angular momentum given to halo gas is approximately universal (Mo et al. 1998). Therefore ρ_{vir} is a good indicator of stellar density ρ_* in a halo.

The Sun formed 9.2 Gyr after the big bang (a redshift of $z = 0.42$). According to the cosmic star formation history, about 90% of all stars formed by the present time (13.8 Gyr) are older than the Sun (Borch et al. 2006), and hence in higher density regions. This also implies the

effect of supernova radiation on life; if this effect is not working, it is statistically more likely to find ourselves in higher density regions than the solar neighborhood. It should also be noted that such regions have more time for evolution of life.

For the first simple calculation of $n(\Lambda)$ with the nearby supernova effect, we estimate stellar densities in the galaxy formation model as follows. Any model galaxy is either the central galaxy in a dark halo or a satellite galaxy trapped by a dark halo as a result of mergers with smaller halos. The density of a stellar population born in a central galaxy is assumed to be $\rho_* \propto \rho_{\text{vir}}$ of the host halo, while that in a satellite galaxy is estimated from ρ_{vir} of the last host halo in which the galaxy existed as the central galaxy. In some cases stellar density would be changed by a galaxy-galaxy merger in a dark halo, but we ignore this effect for simplicity.

The halo virial density of the Milky Way (MW) Galaxy is estimated as $\rho_{\text{vir,MW}} \sim 1.4 \times 10^4 M_{\odot} \text{ kpc}^{-3}$ (Klypin et al. 2002), which can be used as an indicator of ρ_* around the solar neighborhood ($\rho_{*,\odot}$), assuming that the Sun is a typical star formed around the main collapse epoch of the present MW halo. Then we can determine the stellar density relative to the solar neighborhood value as $\rho_*/\rho_{*,\odot} = \rho_{\text{vir}}/\rho_{\text{vir,MW}}$, for all stellar populations formed at each time step in the galaxy formation model. It would be possible to introduce more detailed modelings about internal structures of a galaxy, but they depend on complicated baryon physics and model uncertainties would become large. The primary cosmological effect of Λ to make stellar density higher has reasonably been taken into account by this treatment.

3 Probability Distribution of Λ under the Nearby Supernova Effect

Let N_{exp} for a stellar population be the expected number of sterilizing events during the time for evolution of life to an observer. We introduce a parameter $N_{\text{exp},\odot}$, the value around the solar

neighborhood, which is rather uncertain but of order unity if we consider nearby supernovae. Obviously N_{exp} should increase with stellar density, i.e., $N_{\text{exp}} = (\rho_*/\rho_{*,\odot}) N_{\text{exp},\odot}$. Here, we implicitly assumed that the supernova rate is the same for all stellar populations, though the rate of core-collapse supernovae, which are related to young stellar populations, should be small in old stellar populations. However, type Ia supernovae (SNe Ia) would also affect habitability, which are related to white dwarfs and occur also in old stellar populations (Totani et al. 2008). The SN Ia rate is about ten times lower than the core-collapse rate in MW Galaxy, but they may have more significant effect on habitability because of higher luminosity (Gowanlock et al. 2011). Lethal events occurring in old stellar populations are important in galaxies dominated by such populations, like bulges or elliptical galaxies.

From the Poisson statistics, the probability of survival with no lethal event is $P_s = \exp(-N_{\text{exp}})$. Then $n(\Lambda)$ is calculated by integrating all stellar mass produced in the universe, but with the weight of P_s for each stellar population in a galaxy. Figure 1 shows $n(\Lambda)$ and the probability distributions of Λ for some different values of $N_{\text{exp},\odot}$. The location of the distribution peak is reduced to $\Lambda/\Lambda_{\text{obs}} \sim 4$ when $N_{\text{exp},\odot} = 1$, and $P_o(\Lambda < \Lambda_{\text{obs}})$ is increased to 19%. If $N_{\text{exp},\odot} = 3$, a rather small probability of $P_s(N_{\text{exp},\odot}) = 5\%$ means that we are a lucky survivor, but the distribution peak is further reduced to $\Lambda/\Lambda_{\text{obs}} \sim 2$ with the probability of $P_o(\Lambda < \Lambda_{\text{obs}}) = 41\%$.

4 Discussion

There are still many uncertain aspects about this calculation. The critical distance to a lethal supernova suffers from uncertainties about the effect of high energy particles on the Earth atmosphere, and the degree of damage by ultraviolet light on organisms. Stellar density should be calculated by simulations resolving internal structure of galaxies in future studies, and su-

pernova rates should be calculated by local star formation history in a galaxy. However, the calculation shown here is based on reasonable parameters and treatments, and hence lethal radiation from nearby supernovae must be included in the anthropic consideration about Λ , which may be the only way proposed so far to understand both the extreme smallness and coincidence. Supernovae played an important role for humankind to discover the nonzero cosmological constant (Riess et al. 1998; Perlmutter et al. 1999), but they may also be responsible for its small value.

If there is any physical effect other than supernovae to reduce habitability in high stellar density regions, it would also contribute to making the expected value of Λ_{obs} smaller (e.g., comet bombardment by a field star passage or very wide binary star systems affected by the Galactic potential, see Kaib 2018). Especially, gamma-ray bursts (GRBs) have been discussed as a hazardous astronomical event, whose impact may be comparable or even larger than supernovae (Thorsett 1995; Melott et al. 2004; Piran and Jimenez 2014). GRB rate is much lower than supernova rates, but their luminosity is much brighter, and hence the maximum distance to a lethal GRB is comparable to a typical size of a galaxy. Piran et al. (2016) proposed that lethal radiation from GRBs in nearby dwarf galaxies prohibits an observer to exist in a low Λ universe ($0 < \Lambda \ll \Lambda_{\text{obs}}$), which would be important if the prior Λ distribution is weighted towards smaller values, rather than being uniform per unit Λ . It should be noted that long-duration GRBs (LGRBs) are related only to young stellar populations, but lethal events in old stellar populations are also important to reduce Λ_{obs} by the effect considered in our work. Short-duration GRBs occur also in old stellar populations, like SNe Ia, but their effect on habitability is likely much smaller than LGRBs due to the smaller energy emitted per event. Another important difference from supernovae is that LGRBs occur preferentially in low metallicity regions. Since high stellar density regions are generally metal rich in a galaxy, this should weaken the effect of LGRBs on habitability in high density regions.

If the nearby supernova effect is indeed responsible for the observed small value of Λ as proposed here, a prediction is that we should be located near the edge of habitable regions about stellar density in a galaxy. This may be tested in future by development of observational studies on exoplanets and their habitability. Exoplanets in regions of higher stellar density would show smaller probability of biomarker detection, even if they are apparently habitable.

Acknowledgments

This work was supported by JSPS/MEXT KAKENHI Grant Numbers 15K05018, 17H06362, 17H02867, and 18K03692.

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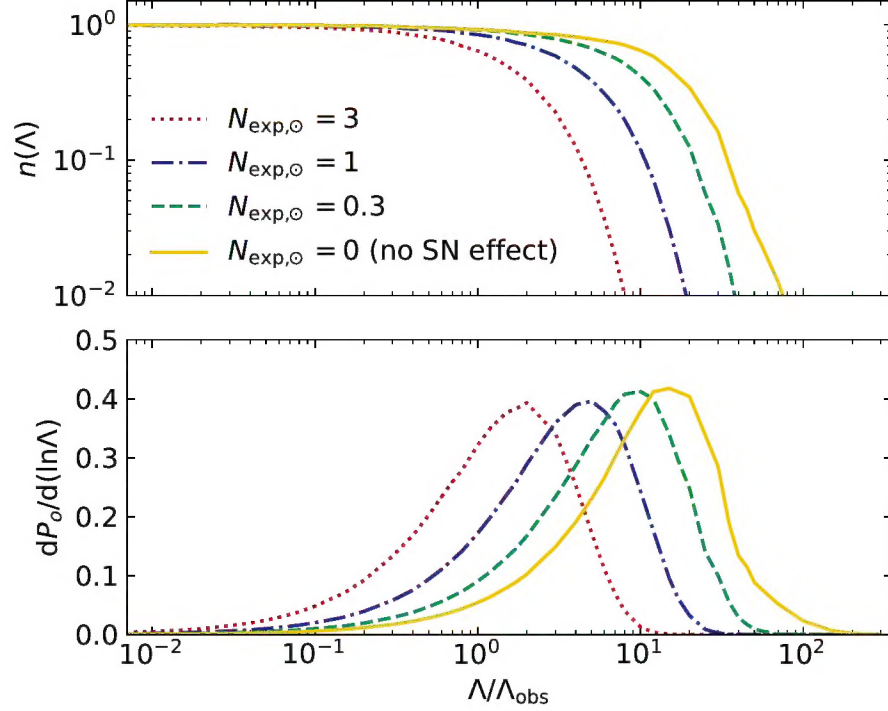


Figure 1: Top panel: the number of observers $n(\Lambda)$ per unit mass of cosmic matter, normalized to unity in the limit of $\Lambda = 0$, for several different values of $N_{\text{exp},\odot}$ (the expected number of lethal events in the solar neighborhood during the time for evolution of life to an observer). When there is no supernova effect (i.e., $N_{\text{exp},\odot} = 0$), $n(\Lambda)$ is proportional to stellar mass produced in the universe up to a cosmic age of 15 Gyr. Bottom panel: the probability distribution of Λ for an observer per unit $\ln \Lambda$, $dP_o/d(\ln \Lambda) = \Lambda dP_o/d\Lambda \propto \Lambda n(\Lambda)$, assuming a flat prior distribution of $dP_p/d\Lambda = \text{const.}$

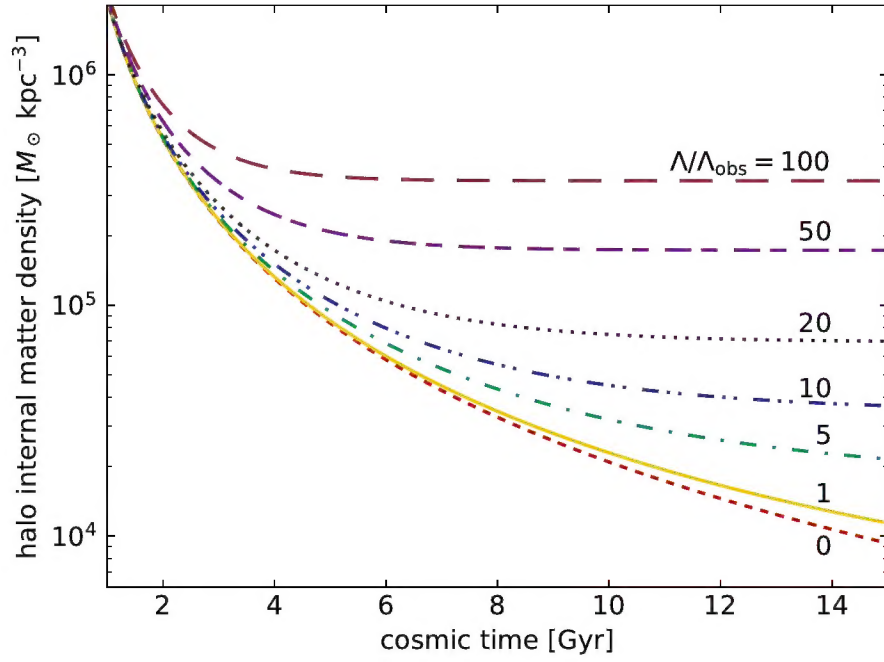


Figure 2: Virial density $M_{\text{vir}}/(4\pi r_{\text{vir}}^3/3)$ of a dark halo as a function of its collapsing time for different values of Λ , where M_{vir} and r_{vir} are the virial mass (baryon plus dark matter) and virial radius, respectively.